SOME PROBLEMS IN HIGH-ENERGY PARTICLE DETECTION AND ANALYSIS

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March 1970

SUMMARY

1. The kinematic analysis of high-energy events requires, in general, particle momentum measurements with an absolute error of ±50-100 MeV/c, independent of momentum. Corresponding errors are 0.05% at 100 GeV/c, less at higher momenta. To minimize the cost of magnetic deflection of high-energy particles, improvements in angular precision, hence, in particle location accuracy, are desirable. The present analysis indicates that improving location accuracy from ±1/3 mm to ±0.1 mm is both desirable and feasible. The usefulness of still higher precision must await data on detailed systems performance.

2. For complex events, it appears likely that vidicon digitization can compete favorably in cost, convenience, and flexibility with large wire-array systems.

3. Neutral particle detectors that furnish accurate data on the location and direction of neutral particles (gamma rays, neutral hadrons) are likely to be important.

I. INTRODUCTION

The new energy region to be explored with the NAL proton synchrotron ranges from about 30 GeV to 200 GeV at first, to 400 to 500 GeV at some later time. In the course of two extensive NAL summer-study sessions at Aspen in 1968 and 1969, some of the problems of detecting particles and measuring events in this broad energy region received a good deal of attention; for further details the reader is referred to the published reports of those two sessions.[1] I would like to review some of the more significant conclusions of the studies and to discuss how they affect preparations now being made for experiments and the electronic detectors required at NAL.

Detailed study shows that a complete kinematic analysis of high-energy events requires absolute momentum accuracy to ±50-100 MeV/c on each particle involved in the event, independent of the total momentum of the event and of the particle momentum, if the overall momentum balance is to be sufficiently accurate to ascertain whether or not a single neutral pion, of mass 135 MeV/c^2, is missing. The inability to determine whether a particle is missing makes a definite kinematic fit impossible, and while some experiments can occasionally be designed in which kinematic fits can be dispensed with, that is not the normal situation. Consequently, if kinematic fits are to be used in identifying the reaction, the momentum accuracy specified implies measurement precision in the range 0.025-0.05% for particles around 200 GeV/c. As we will see, this imposes strict requirements on the accuracy demanded from particle location devices, as well as on system engineering and layout.

At lower energies there has been a tendency to ignore reactions in which neutral products had to be detected to analyze the event. At high energies it becomes much more difficult to ignore neutrals, since few events are free from them. Detectors for gamma rays and neutral hadrons therefore assume heightened importance; we shall discuss them further.

There is also a very difficult particle indentification problem, since at ultra-relativistic speeds all particles tend to look alike. Detectors that determine the particle mass in the relativistic region--for example, by measuring γ rather than β--therefore assume new importance. No established solution to this problem exists.

In the remainder of this paper we discuss the achievement of high precision in momentum measurements, the digitizing of complex events, and we will review progress in the detection and measurement of neutral particles.

II. ACHIEVEMENT OF HIGH SPATIAL RESOLUTION: SYSTEMS CONSIDERATIONS

To achieve a momentum accuracy of 0.05% or better, the angular deflection of a particle in a known magnetic field must be measured to that precision. A "deflection" system (see Fig. 1), in which the angular deflection is determined by measuring the direction of the particle both before and after magnetic deflection, is cheaper[2] than an "immersion" system, in which the trajectory lies within a large magnet and the radius of curvature must be determined. A suitable deflecting system for high-momentum particles must then bend the particle through an angle several thousand times greater than the error in determining the particle's initial and final directions. We illustrate the economics of momentum measurement by a simplified example.

A 100-GeV/c particle is deflected 0.3 mrad by each kG-meter, or 3 mrad by each tesla-meter (T · M) of magnetic field path. Fortunately, the deflecting magnets used in high-energy experiments tend to be relatively inexpensive; the dynamics of the reaction projects fast particles forward, so that the magnets do not require a large aperture. Current NAL deflecting magnet designs cost about \$5 K per T · M.[3] Wire-chamber practice determines the incident and outgoing particle directions by locating (effectively) two points on each line, with the conventional one-third mm accuracy. If the points are 10 m apart on each line, each direction is determined to 46 μrad, and the overall deflection angle to 67 μrad. Then, neglecting other sources of angular error, the 0.05% momentum accuracy required prescribes a bending angle of 133 mrad and a magnetic path of 43 T · M. The magnet cost is then \$215 K. Were we to double the accuracy of measurement of the bending angle, that angle could be halved, and with it the magnet cost.

Consequently, accurate angular measurement is of the utmost economic importance, up to the point where the increasing cost of higher accuracy outweighs magnet savings. We cannot increase lever arms without sacrificing aperture and therefore rate.

Let us next examine other sources of angular error, which limit the degree to which overall improvements can be achieved by spatial accuracy alone. They include multiple scattering, surveying errors, thermal stability, and accuracy of magnet calibration. At 100 GeV, a thickness of one radiation length produces a mean scattering angle of 150 μrad, and the angle is proportional to the square root of the thickness. If we try to decrease the overall error to 20 μrad, the maximum tolerable scattering mass for a 15 μrad scattering error is 0.01 radiation length, which is about 0.5 g/cm^2 of low-Z material such as plastics. We cannot go much further.

Another limit to the precision is the accuracy and stability of the magnetic path length $\int Bdl$. It is difficult, in actual operation, to achieve an absolute precision exceeding 1 part per thousand. It is general practice to calibrate spectrometer magnets with beam particles, using overdetermined reactions like p-p scattering to obtain more accurate values of $\int Bdl$.[7]

Thermal expansion coefficients of structural materials are in the range 10^{-5} per degree, giving 0.1 mm changes of length of one-meter long chambers for 10° C temperature changes. Fiducial systems for locating and checking component positions require careful design.

Momentum-determining spectrometers of this sort have already been built and used at lower momenta. At 30 GeV/c spectrometers[6] with overall angular accuracies of ±75 μrad have been built and used, with sonic chambers and on-line recording of data. Bowen et al.[7] have reported a high-precision 1 GeV/c spectrometer used at Berkeley, with momentum resolution 0.05%. At such low energies such performance requires very careful attention to alignment and scattering as well as location accuracy, and less thought to magnet economy. The spectrometer utilized photographic recording of wide-gap spark chambers. Despite great care, it was found that although the desired relative precision was obtained, an absolute correction of 0.35% to the momentum was needed.

The frequent occurrence of such systematic errors induces caution concerning order-of-magnitude jumps in precision. It seems inadvisable to aim for much better than about 0.1 mm spatial accuracy in the spark chambers before achieving corresponding overall system errors in a working system. Detailed quantitative considerations of these questions have been given by Jones,[4] Osborne,[2] and others.[5, 7]

III. MEANS FOR IMPROVING SPATIAL RESOLUTION

Alvarez, in an unpublished momorandum,[8] suggested the reinvestigation of ionization chambers using liquid argon, with a view to capitalizing on the approximately thousand-fold increase in density to improve spatial resolution by a factor of the order of 100 or more. The requirement for this kind of resolution (a few microns in space) arises from the desire to extend cosmic-ray measurements with balloon-borne magnets to as high a momentum as possible. The progress of this work has been recently described in a paper by Derenzo et al.[9]

However, improvements up to one order of magnitude, such as we are considering here, do not require anything like so much increase of density. Scaling the usual gas discharge parameters, one would expect that a moderate increase in density, whether produced by higher pressure or lower temperature, might allow the required improvement of precision. Indeed, it is by no means clear that the current canonical value of one-third mm error for wire chambers is imposed by the fundamental nature of the gas discharge, rather than the particular technology currently employed for reading out positions--especially, the scale of digitization used in wire chambers. Consequently, improvements of the amount sought may well be possible without excessive difficulty.

Several groups have already made important steps in this direction. J. Fischer et al.[10] reported a spatial accuracy of 70 microns, using fine wire spacings (4.5 wires/mm), 1.6 mm gaps, and slow protons with $10 \times$ minimum ionization. Minimum ionizing particles in the same gas at ten times the density can reasonably be expected to yield similar results. The increased density can be obtained either by decreasing the temperature or increasing the pressure. Experiments with narrow wire spacings (200 wires/inch) and high-pressure gas fillings are being conducted at Yale by Willis, Winters et al.,[11] and elsewhere. Narrow wire spacings introduce difficulty in magnetostrictive wire readout systems, since the inconveniently high speed of sound in nickel (5 mm/μsec) demands either very high clock rates (e.g. 100 MHz[10]) with correspondingly expensive scalers, or fanning out the wires before readout to increase the time interval between wires (Yale[11]).

Earlier work with high-pressure fillings has shown that, as might be expected, high pressure converts a narrow-gap chamber into a wide-gap chamber. Akopyan et al.[12] found that a 10-mm gap spacing, giving only sampling sparks along the electric field at one atmosphere, gave delineating tracks following the particle trajectory up to angles exceeding 30° at 5 atmospheres.

No experiments at increased densities have been reported as yet on the improvement in track localization to be expected; earlier measurements at high pressure[12, 13] and low temperature[14, 15] emphasized the increased efficiency obtained.

Accuracies exceeding 0.1 mm for chambers at atmospheric pressure have already been observed in wide-gap chambers,[4, 16, 18] and in sonic chambers[19] (which also profit in accuracy from much slower signal propagation in the readout medium). In the former case, accuracies of 0.1 mm have been achieved in an experiment with cosmic rays,[4] although not yet in an accelerator situation. Thus it seems clear that the achievement of the desired precision is likely to be primarily a systems engineering problem.

IV. DIGITIZATION OF LARGE-SCALE EXPERIMENTS

Another problem, not unique to very high energy experiments, but particularly acute there, is that of digitizing and storing the data on rather complex events. At lower energies, complex events have most often been studied in bubble chambers, and only recently has it been proposed[20, 21] to do direct digitization and on-line recording of events as complex as associated production:

$$\pi^- + p \rightarrow \Lambda^o + K^o, \qquad \Lambda^o \rightarrow p + \pi^-, \qquad K^o \rightarrow \pi^+ + \pi^- .$$

At the hundred-BeV energy domain, the analysis of events in bubble chambers becomes increasingly unrewarding, as the possible number of different channels and the required precision increase rapidly, and the probability of a given event being analyzable approaches zero. Consequently, even for relatively complex events, electronic detection techniques now appear to be favored.

However, on-line digitization and recording can be accomplished by means other than wire arrays; in fact, two other digitization methods pre-date wire-array systems, namely sonic detection and vidicon detection. In view of the high costs of large wire-array systems, re-examination of alternative systems seems worthwhile. In a paper in the 1969 Aspen Summer Study, the author[22] re-examined the vidicon storage and digitizing method in the light of increasing wire-array costs and improvements in vidicon resolution and sensitivity. Unless costs can be cut, large wire array systems will probably not be able to compete economically with the on-line vidicon digitization system. Recent improvements in vidicons, both in sensitivity and resolution, have made them much more attractive, and it is now possible to demonstrate that for a sufficiently large and complex system, vidicon digitization of wide-gap optical chambers must be cheaper than a wire-array digitization system. It will have the additional advantage of complete flexibility and easy direct computer control of the digitization, even including event-dictated digitization procedures. It cannot compete in repetition rate, but with events of the complexity considered here, this is not usually a serious consideration. The cost crossover is difficult to determine, since no working high-resolution vidicon system exists; it appears likely, however, that it may well occur for systems smaller than Lindenbaum's, and a fortiori for monster systems like that described by Leith et al.[20]

V. NEUTRAL PARTICLE DETECTORS

Traditionally, neutral particle detectors have been either of the absorption or spectrometer types. At energies above a few MeV, gamma-ray spectrometers rely upon pair production in a thin radiator, and measure the momentum of the electron pair produced, by means of a magnetic field. Proton recoil spectrometers are similarly used for neutrons up to a few hundred MeV. Such spectrometers require a direct trade-off between efficiency and resolution; high resolution is attainable only with thin radiators and low efficiency which greatly diminishes their applicability in most high-energy applications (see, however, Cronin's use in K^o-decay).[23] In addition, total-absorption gamma-ray detectors have now reached resolutions of one or two per-cent and can be expected to do even better at higher energies, so that gamma-ray spectrometers are now virtually obsolete except for special applications.

Total-absorption detectors of neutral particles are designed to contain the cascade initiated by the primary, to the extent necessary to achieve the efficiency and resolution required.[24] The cascade process is subject to large random fluctuations of track density and penetration, and depends also on the nature and density of the absorbing medium. Consequently, the resolution will depend not only on the statistics of the signal produced--photoelectrons at a photocathode in the case of scintillators, numbers and distribution of sparks in spark chambers--but also on the inherent fluctuations. The magnitude of these fluctuations is sufficiently large that a sampling process in which the cascade is judiciously sampled at various depths may well yield as good resolution as does total absorption in a scintillator.[25, 26]

The characteristic development of a gamma-ray cascade is shown in Fig. 2. The gamma-ray cascade, which consists primarily of gamma-ray $\leftrightarrow$ electron-pair interchanges via bremsstrahlung and pair production, is much simpler than the nuclear cascade, and both theoretical and Monte Carlo descriptions have been given that are in adequate agreement with experiment. The designer of a gamma-ray cascade detector has a choice of scale since the radiation length of different materials varies as Z^{-1}, being about 10 m in liquid hydrogen and 5.5 mm in lead.

A major characteristic of cascade total absorption detectors is that their size varies only logarithmically with energy. Since containment of even moderately low-energy cascade requires many cascade lengths, a single design will work well over several decades of energy.

The nuclear cascade is nowhere as well understood as the gamma-ray cascade. An overall behavior like that of Fig. 2 is certainly to be expected, but its details are still largely unexplored above 10 GeV.[24, 26, 27] The collision length for hadrons is about 100 g/cm^2, nearly independent of Z and the kind of interacting particle. To contain a hadron cascade with ten collision lengths, therefore, takes of the order of 1 kG/cm^2, or ten tons if the area of the detector is one meter square. Smaller detectors are possible for collimated beams, but clearly we are dealing with hundreds, if not thousands, of kilograms of material. Economics therefore urges us strongly in the direction of inexpensive materials like lead or iron, rather than NaI crystals.

However, the simplest total-absorption cascade detectors are the homogeneous scintillators, such as PbF, and NaI, which yield excellent results for gamma rays,[28, 29] and in sufficiently large sizes will probably do the same for neutral hadrons.[29] These detectors are functional counters, with a single output pulse whose height yields the incident particle energy. Their chief drawbacks are high cost, slow decay, and possible nonlinearity for the slow nucleonic component of hadronic collisions. A sampling detector, which interleaves absorbers and scintillators, may do as well if it achieves adequate sampling;[30, 31] this in turn depends on the unknown fraction of energy going into the short-range slow nucleonic component, which is hard to sample with absorbers of finite thickness. Clearly, a great deal of exploratory work still remains to be done.

VI. DESIGN OF NEUTRAL PARTICLE DETECTORS

Improved detectors of high-energy gamma rays and neutral hadrons are under active development in many laboratories. In addition to an intrinsic detection efficiency of 90% or more, the detector may be asked in different experiments to signal the following information:

1. The existence of one or more neutral particles (for triggering purposes).

2. Both the existence and the number of neutrals--thus distinguishing, say, two gamma rays or neutrons from a single one.

3. Location of the point of interaction of each neutral in the detector.[32] If the source is known, this give the direction of the neutral particle. Knowing the particle direction provides two of the three possible kinematic constraints available from knowing the particle vector momentum; the particle energy or momentum provides the third, if known.

4. Location of the point of interaction and measurement of the direction of each neutral; this gives the particle direction without knowing the source, which can therefore be identified if there is ambiguity (as in a multi-vertex event).

5. The energy only of the neutral--providing one kinematic constraint. Finite detector size usually gives some information on direction as well, though it may be inadequate for kinematic use.

6. Measurement of both energy and direction--either point-of-interaction alone or both point-of-interaction and direction for each neutral. Such a detector provides all three kinematic constraints. If two or more neutrals are present, good resolution and individual measurement on each neutral are desirable. This is the maximal kinematic information to be expected.

Gamma-ray detectors are now possible that satisfy any of the requirements listed above; they increase in cost and complexity as the information required becomes more detailed.

If we categorize detectors according to the above schema of information requirements, current practice with gamma-ray detectors stands about as follows:

1. Gamma-ray counters, signaling the existence of one or more gamma rays, with an output signal proportional to total energy, can be made from either lead glass, PbF Cerenkov radiators,[28] large NaI scintillation crystals,[28] or lead-scintillator sandwiches; the latter is the cheapest, and its performance at energies up to 15 GeV compares well with that of NaI. Hodoscopes of such detectors provide limited spatial resolution. Very high energy resolution (1% fwhm at 14 GeV) is possible.[24]

2. Spark chambers, with radiators alternating with either visual chamber gaps or wire arrays, provide information on the location of the point of interaction of the gamma ray. The number and distribution of the sparks also provides information of the energy of the cascade,[33] and different gamma rays can be distinguished if the cascade of one does not obliterate the interaction of another. Sampling at intervals of one radiation length is adequate if intrinsic directional information is not needed.

3. Sampling at intervals of 1/5 to 1/10 r.l. will allow determination of the gamma-ray direction to one degree of better; 8 mrad has been reported.[34]

4. Combined radiators, spark-chamber gaps, and scintillators provide fast triggering data on total energy in addition to spatial resolution. Several systems of this sort are being tested.

As to neutron detectors, most current work has been done with absorber-scintillator sandwiches. In cosmic-ray work this type of detector is called on ionization calorimeter.[26] Recently spark chambers of the visual type have been used,[32] and now wire arrays for direct readout are being added.[11] It is difficult to design chambers of this type, since not enough is known about the detailed characteristics of the cascade process, such as the fraction of energy in very short-range nucleons, their angular distribution, the fraction of energy fed into electromagnet cascades via neutral pions, etc. To date, observations on ionization density in nucleonic cascades do not agree with theoretical predictions.[24, 27] This is an active field and is changing rapidly; since current interest in detecting neutral particles in high-energy collisions is higher than ever before, we can expect significant progress in the near future. The best energy resolution obtained to date is a 20% fwhm reading at 30 BeV/c (actually obtained with protons), achieved at CERN by the Karlsruhe group.[31]

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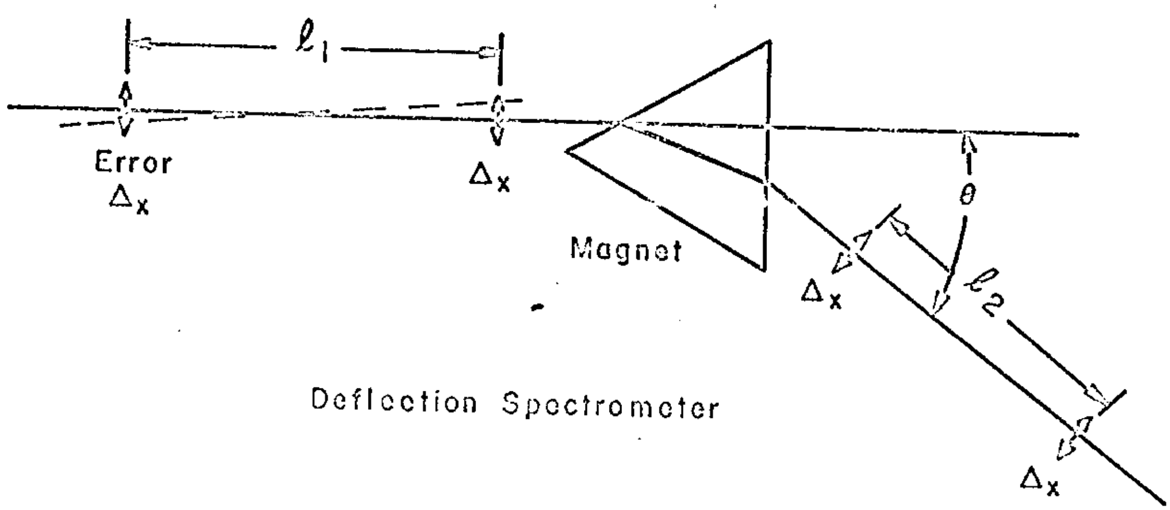

Fig. 1. Momentum determination with a deflection spectrometer, showing sources of angular error.

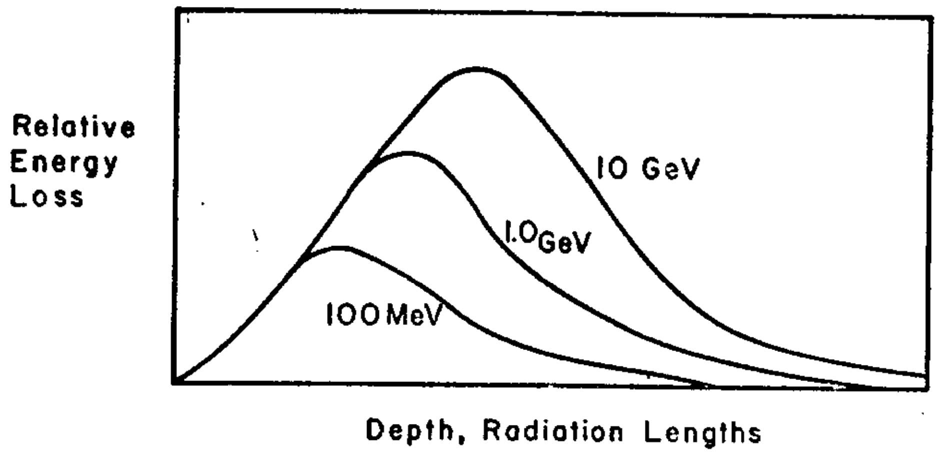

Fig. 2. Rate of energy loss in high-energy showers and hadron cascades.